NDIA 6th Annual Systems Engineering Supportability & Interoperability Conference

STOCHASTIC SIMULATION

A NEW TOOL FOR ENGINEERING

Gene Allen & Jacek Marczyk

MSC.Software

October 22, 2003

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PRESENTATION PURPOSE

INTRODUCE NEW ENGINEERING METHOD

- ENABLED BY ADVANCES IN COMPUTERS
- USES STOCHASTIC SIMULATION
- MODELS REFLECT REALITY IN TEST

SHOW HOW METHOD IS BEING USED BY INDUSTRY

- REDUCES RISK AND COST

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INTRODUCTION

Gene Allen

- **Develop/Commercialize manufacturing technologies**
- **Director, Collaborative Development, MSC & NCMS**
- **Economic Development & Defense Procurement Assistant, Senator Byrd**
- **U.S. Navy Nuclear Background**
- **B.S. Nuclear Engineering, MIT**

Dr. Jacek Marczyk

- **Foremost practitioner of Stochastics**
- **Established & managed EU Promenvier Project at CAS**
- **Took Results to Auto Industry**
- **Applied Stochastics to crash**
- **Working next generation stochastic product**

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PRESENTATION OUTLINE

- THE CHALLENGE
- STOCHASTICS PROCESS
  - Uncertainty
  - Monte Carlo Simulation
  - Results (Meta Model)
  - Design Improvement
- INDUSTRY APPLICATIONS
- IMPROVED ENGINEERING

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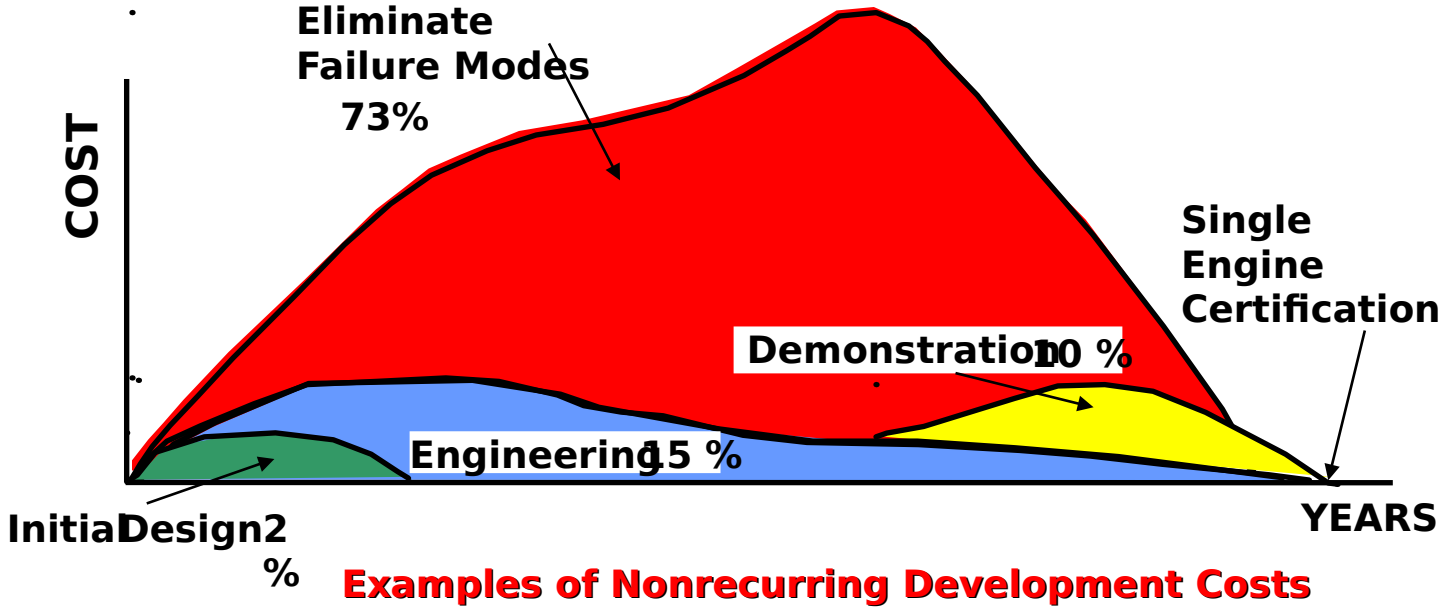
COST TO FIRST PRODUCTION

~~DOMINATED BY ELIMINATING FAILURE~~ MODES



Examples of Nonrecurring Development Costs

Rocket Engines

- **SSME** $ 2.8 B
- **F-1** $ 2.4 B
- **J-2** $ 1.7 B

Jet Engines

- **F-100** $ 2.0 B

Automobiles

- **1996 Ford Taurus** $ 2.8 B

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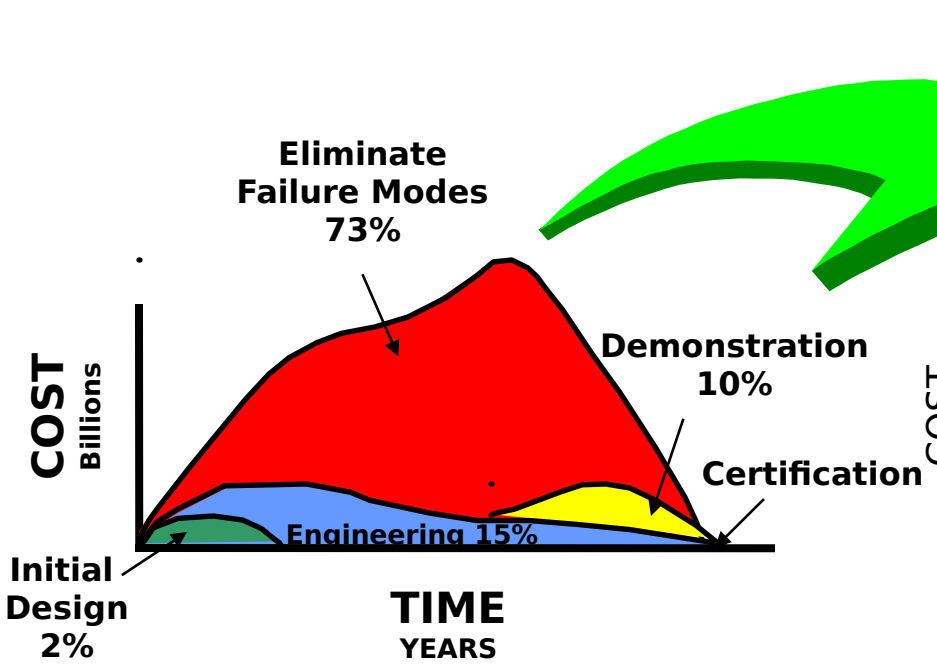
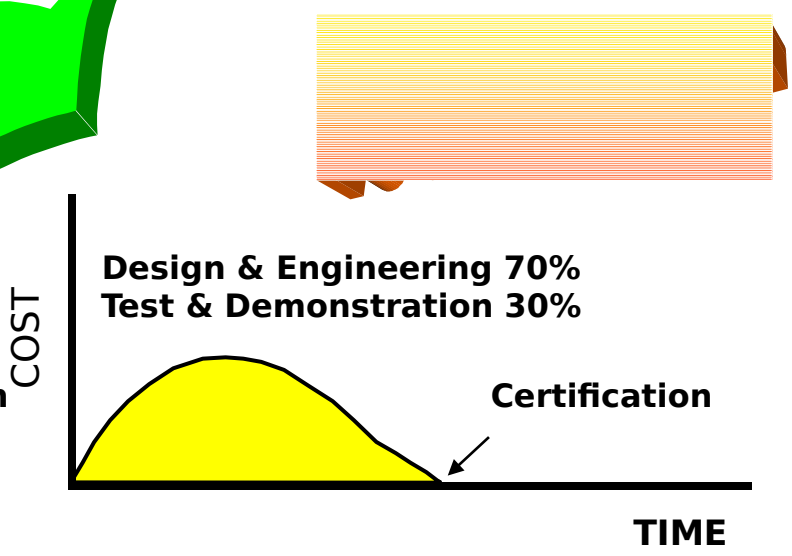
Computer Engineering Vision





Historic Cost-Time profile for aerospace/automotive platforms

Vision of 75% reduction in Cost-Time profile to be realized through use of computers

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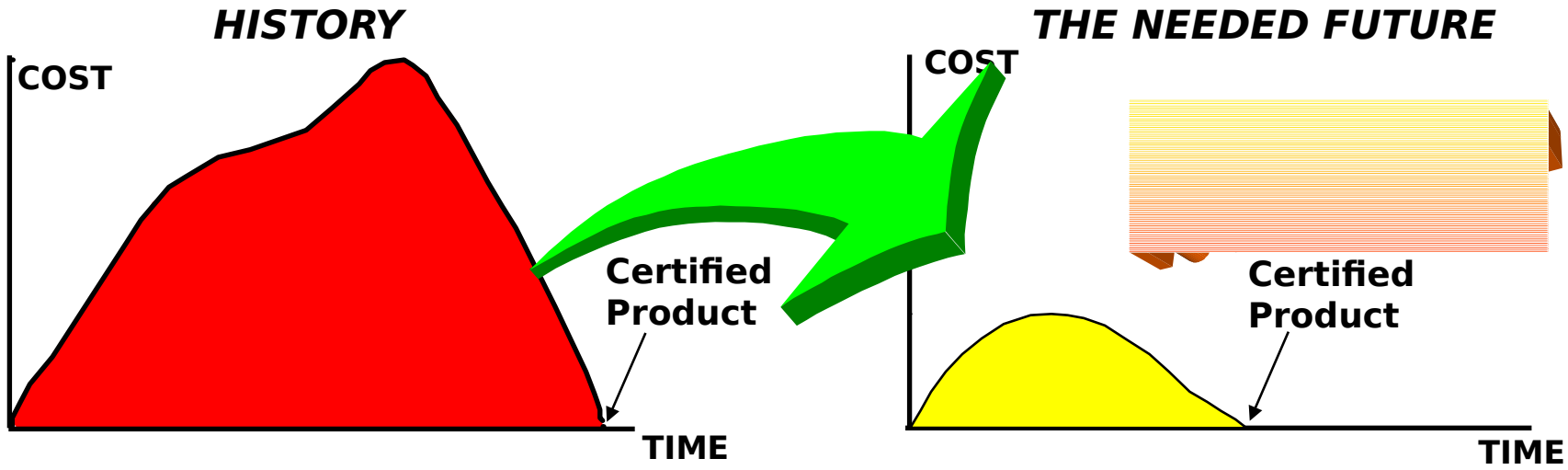
THE PATH TO LOW COST DEVELOPMENT



THIS VISION HAS NOT BEEN REALIZED

WHY? - LACK OF CONFIDENCE THAT MODELS CAN REPLACE

WHY? - MODELS have been DETERMINISTIC while REALITY IS STOCHASTIC

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U.S. Army Recognition

Gen Kern attended 10-06-03 SAE G-11 meeting in Detroit

- **Relayed that the Army's environment is probabilistic.**
- **Lack of reliability of Army platforms is costing taxpayers multi-billions of dollars.**
- **Equipment breakdowns have lead to soldier's deaths in Iraq**
- **Model reliability versus test**
  - **For systems fielded between 1985 and 1995 41% met their reliability targets during test.**
  - **For systems fielded from 1996 to 2000 only 20% met their reliability targets during test.**

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The Stochastic Method

- Incorporates Variability and Uncertainty
- Based on Monte Carlo Simulation
  - Updated Latin Hypercube sampling
- Independent of the Number of Variables
- Generates a Meta Model
- Does Not Violate Physics
  - No assumptions of continuity
- “Not elegant, only gives the right answers.”

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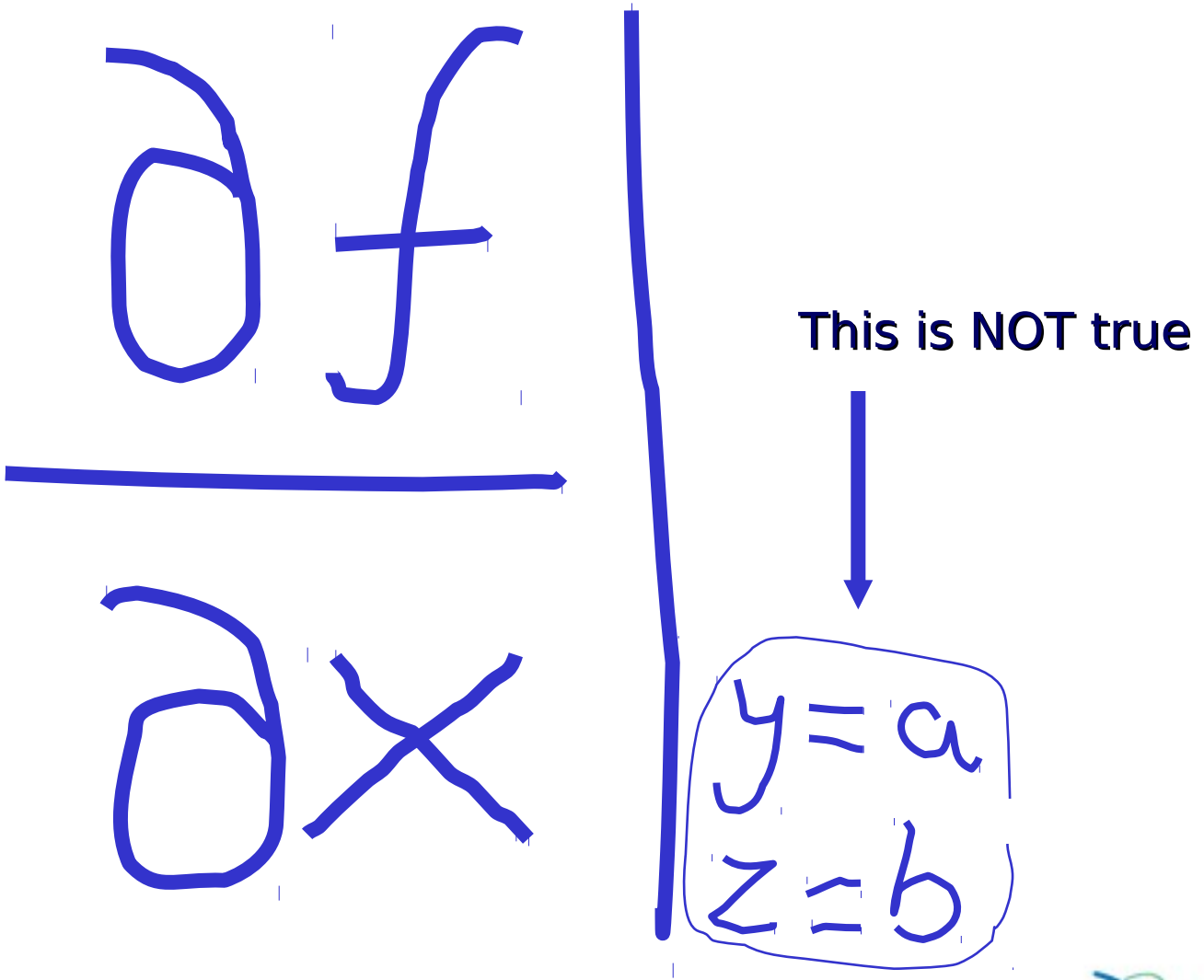
Example of Physics Violation



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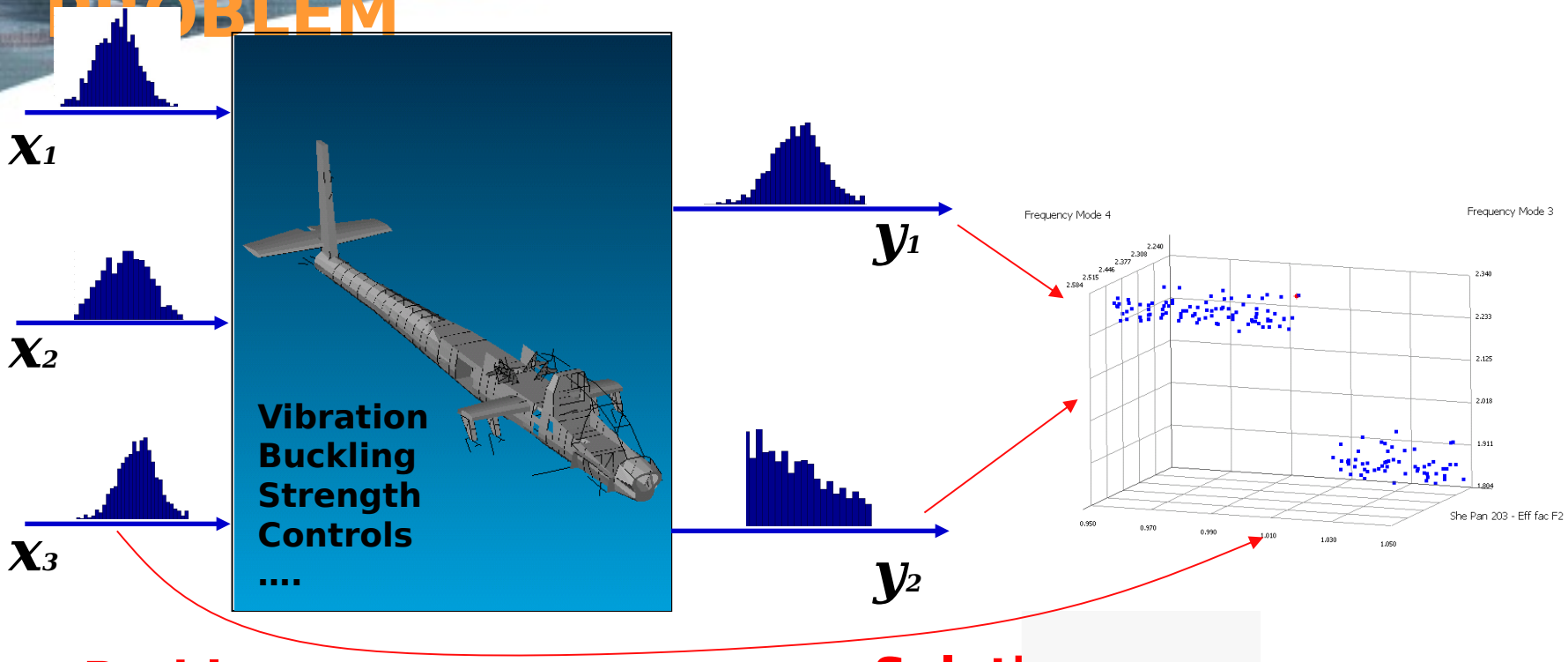
DEFINITION OF A STOCHASTIC PROBLEM



Problem:

Given a set of uncertain design/input variables, determine the level of uncertainty in the response variables.

Solution:

Establish tolerances for the input and design variables. Run a Monte Carlo simulati in order to obtain the syste response in statistical term

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Sources of Uncertainty

- Material Properties
- Loads
- Boundary and initial conditions
- Geometry errors
- Assembly errors
- Solver
- Computer (round-off, truncation, etc.)
- Engineer (choice of element type, algorithm,
  mesh band-width, etc.)

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Structural Material Scatter

MATERIAL	CHARACTERISTIC	CV
Metallic	Rupture	8-15%
	Buckling	14%
Carbon Fiber	Rupture	10-17%
Screw, Rivet, Welding	Rupture	8%
Bonding	Adhesive strength	12-
	Metal/metal	8-13%
Honeycomb	Tension	16%
	Shear, compression	10%
	Face wrinkling	8%
Inserts	Axial loading	12%
Thermal protection (AQ60)	In-plane tension	12-
	In-plane compression	15-

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Load Scatter (aerospace)

LOAD TYPE	CV	ORIGIN OF RESULTS	
Launch vehicle thrust	5%	STS, ARIANE	
Launch vehicle quasi-static loads	30%	STS, ARIANE, DELTA	
- POGO oscillation - stages cut-off - wind shear and gust - landing (STS)			
Transient	60%	ARIANE 4	
Thermal		Thermal tests	8-20%
Deployment shocks (Solar array)	10%	Aerospatiale	
Thruster burn		Calibration tests	2%
Acoustic		ARIANE 4 and STS (flight)	30%

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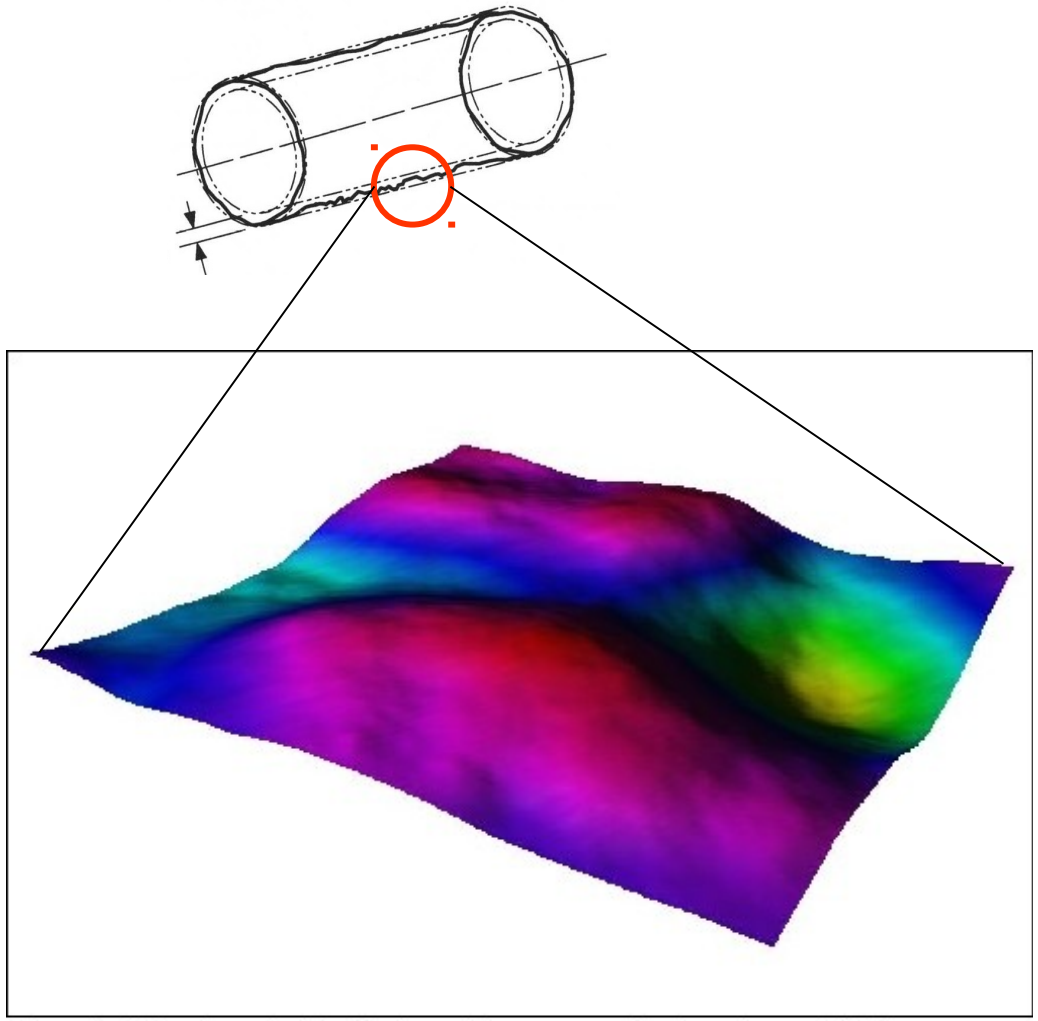
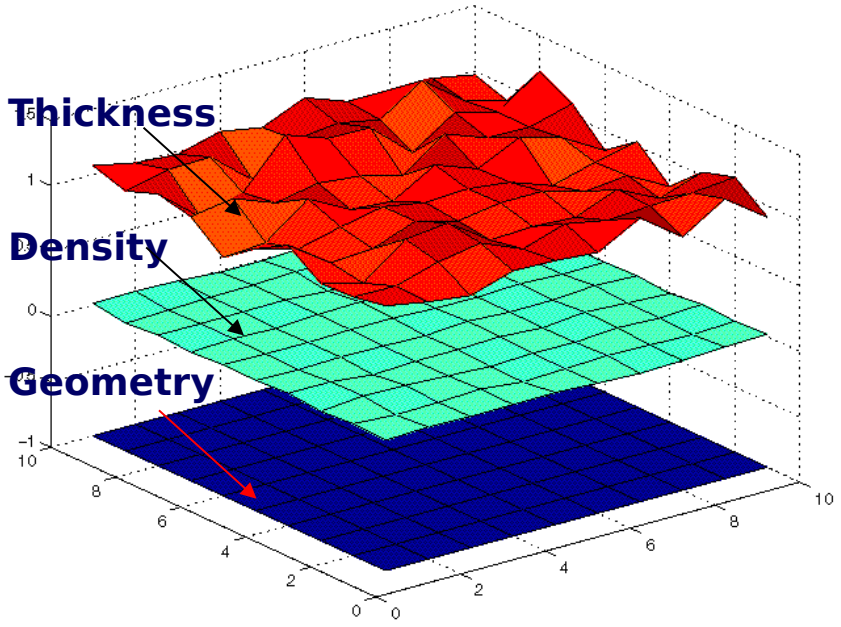
The Deception of Precise Geometry

Geometry imperfections may be described via stochastic fields.





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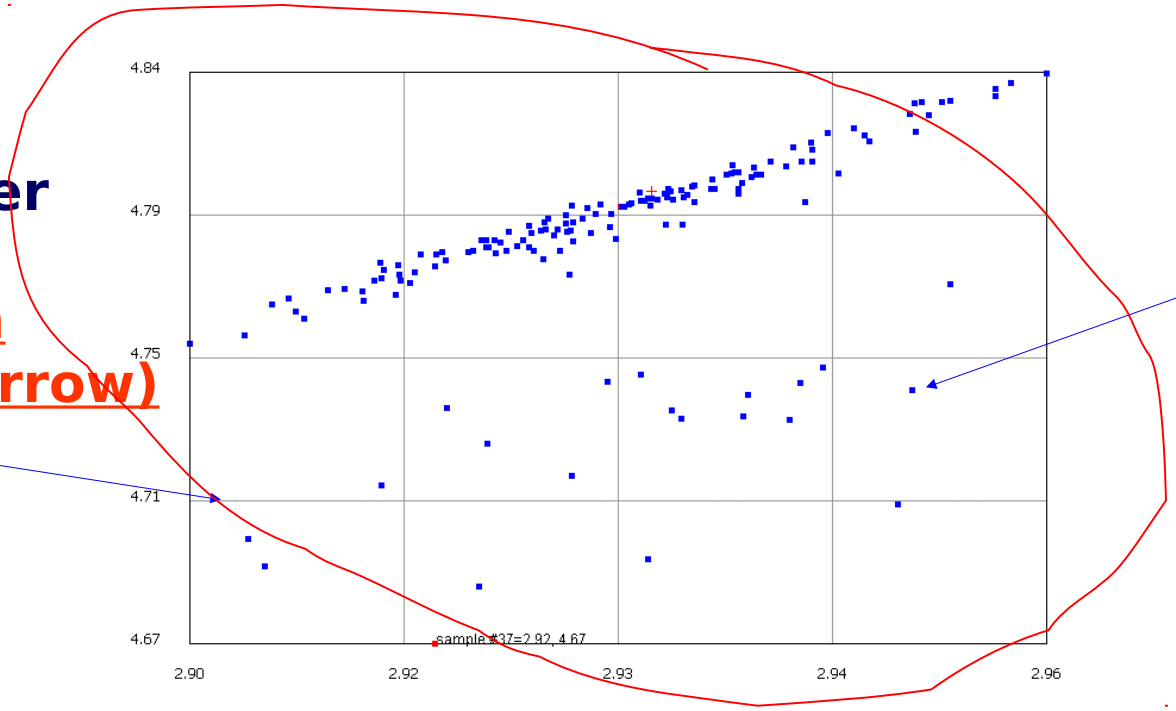
The Concept of a Meta-Model

Collection of computer runs = Simulation (CAE tomorrow)



Single computer run = Analysis (CAE today)

Understanding the physics of a phenomenon is equivalent understanding of the topology and structure of these cloud

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Example of Meta-Model (13D)

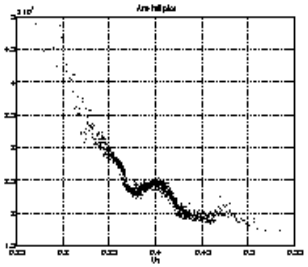
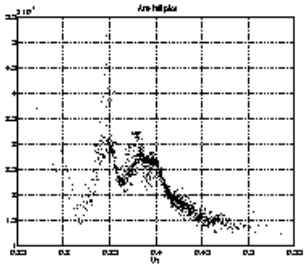



Figure 1.16: σ_{Tx} (left) and σ_{Ty} (right) versus thickness.

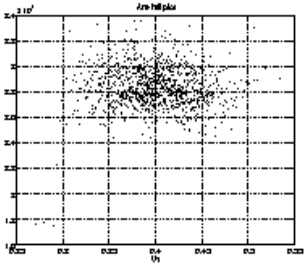
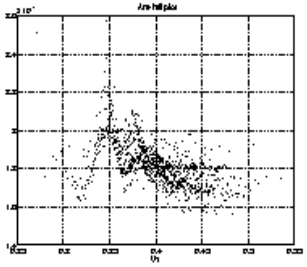



Figure 1.17: σ_{Tz} (left) and σ_{Rx} (right) versus thickness.

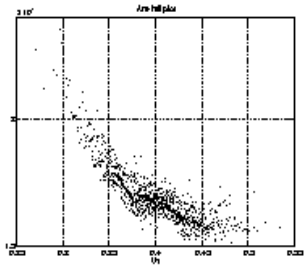
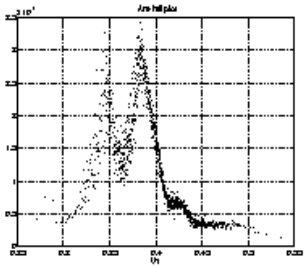



Figure 1.18: σ_{Ry} (left) and σ_{Rz} (right) versus thickness.

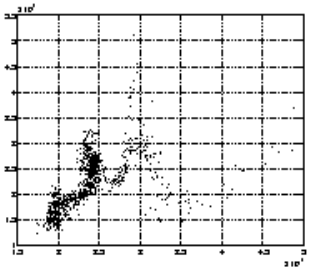
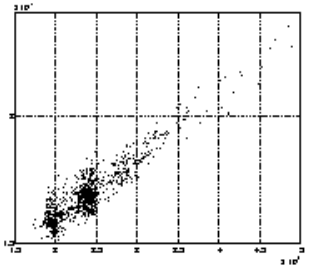



Figure 1.20: σ_{Tx} versus σ_{Ty} (left) and σ_{Tx} versus σ_{Ry} (right).

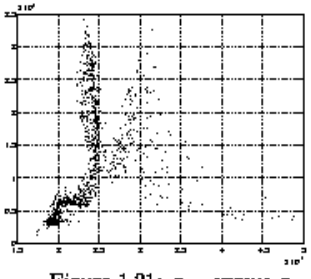
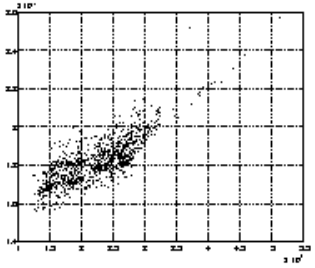



Figure 1.21: σ_{Tx} versus σ_{Rz} (left) and σ_{Ty} versus σ_{Rx} (right).

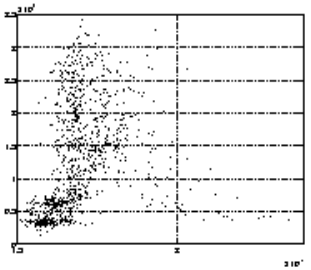
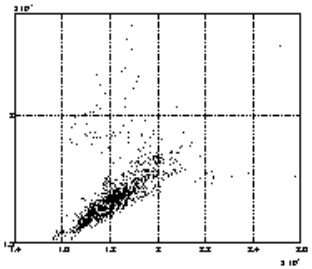
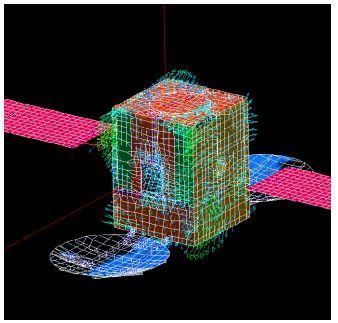



Figure 1.22: σ_{Ry} versus σ_{Rz} (left) and σ_{Rx} versus σ_{Ry} (right).



7 inputs and 6 Outputs. The meta-model is result of a scan with uniform distributions.

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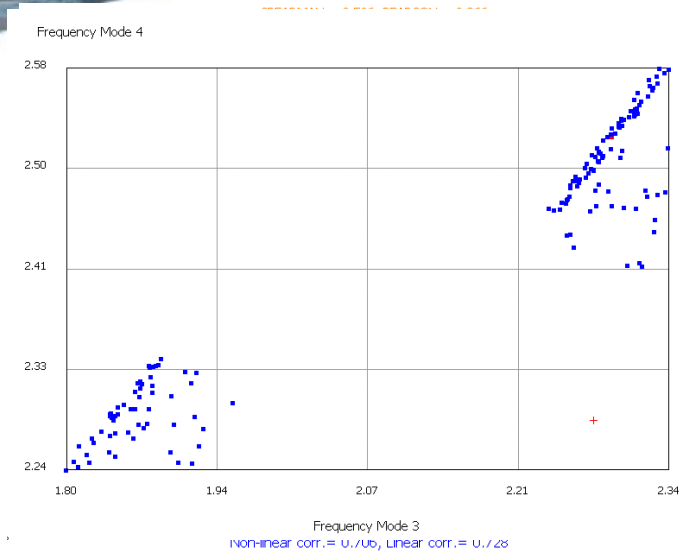
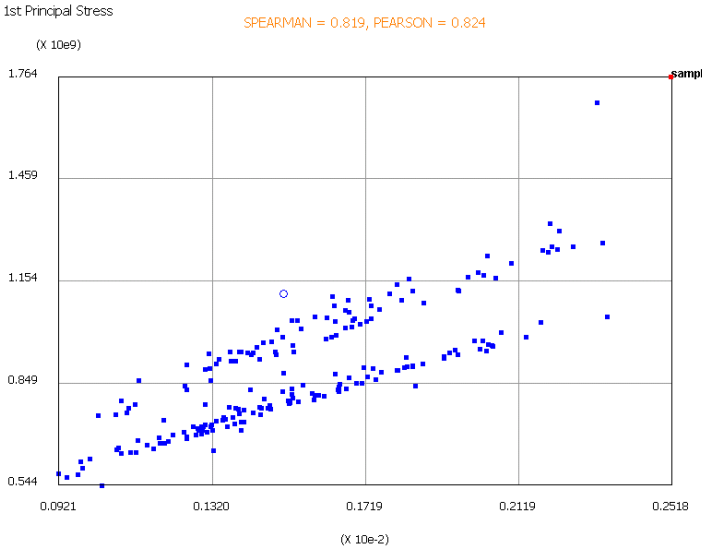
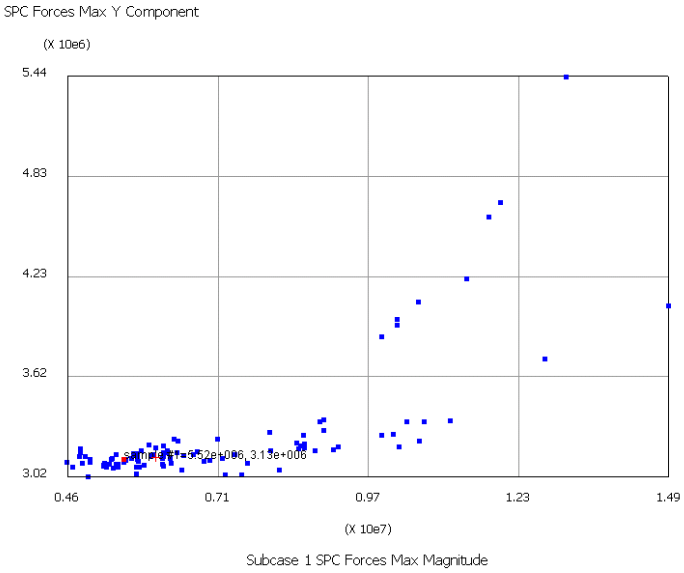
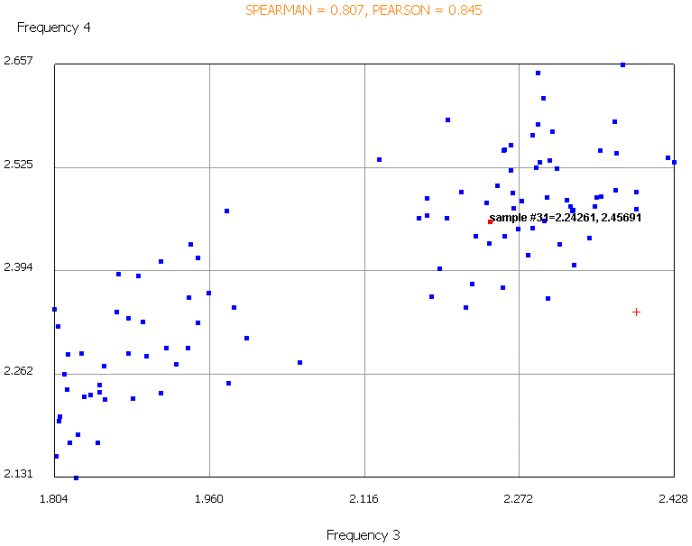
Clustering (Bifurcations)









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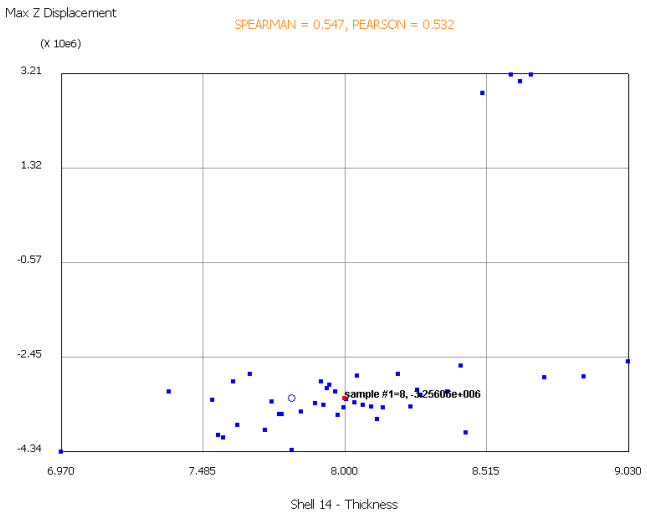
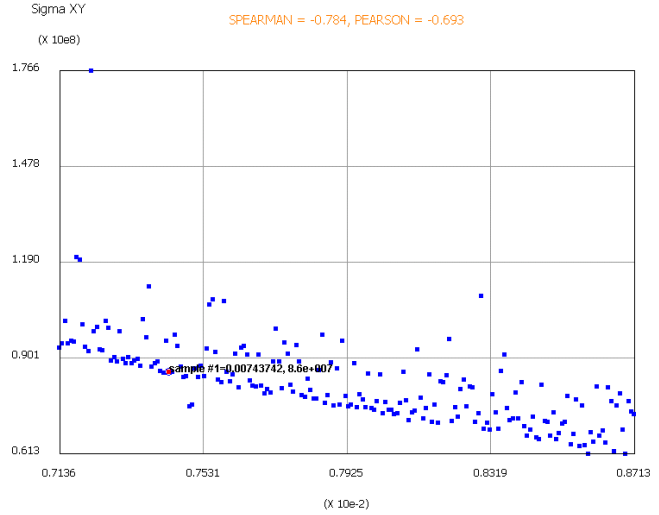
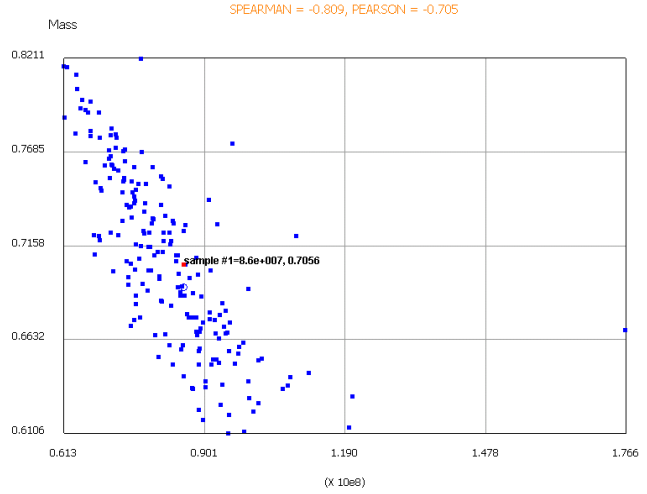
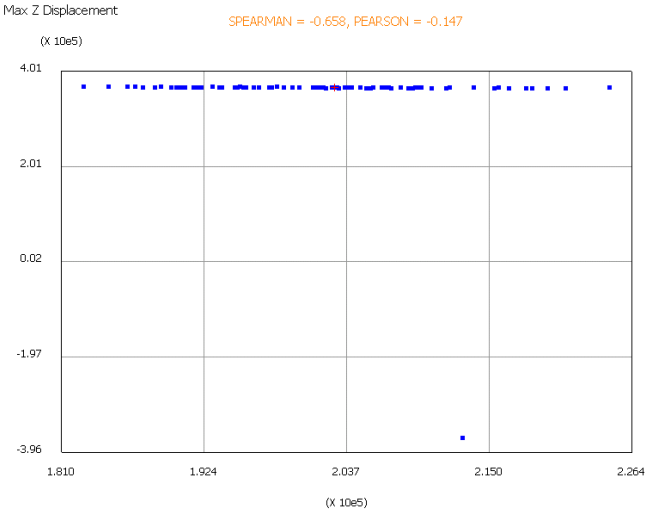
Outliers









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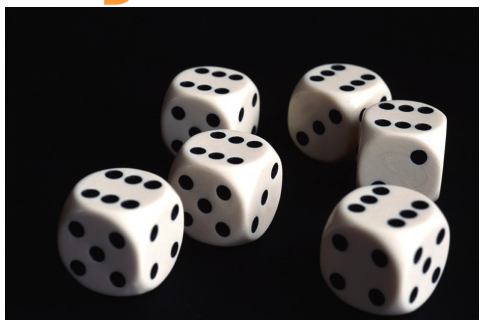
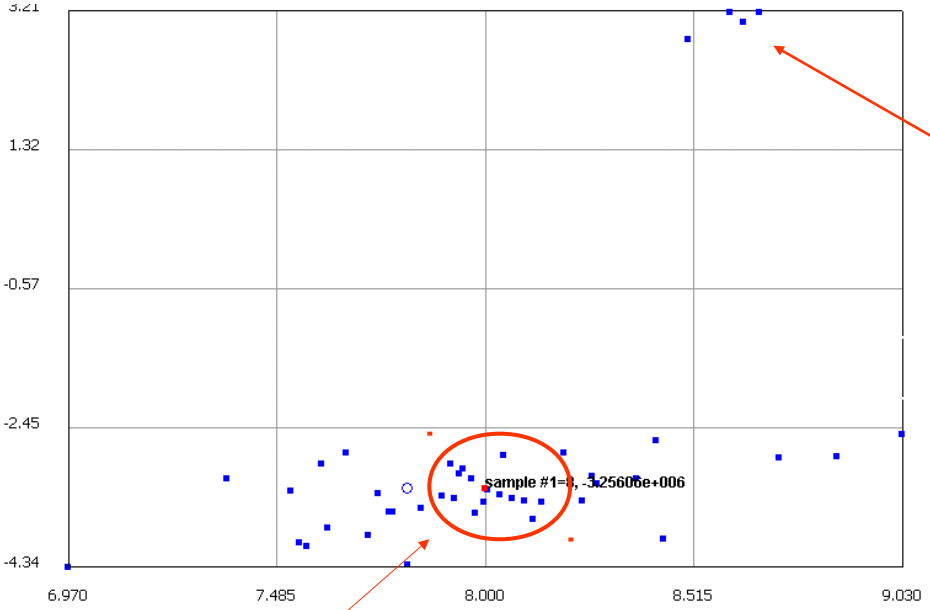
Why Stochastic Analysis





Outliers: may be dangerous:
- Lawsuit
- Warranty
- Recall

Most likely behavior

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Understanding the Meta Model

KEY:

- **REDUCE the Multi-Dimensional Cloud to EASILY UNDERSTOOD INFORMATION**

CLOUD:

- **POSITION provides information on PERFORMANCE**
- **SCATTER represents QUALITY**
- **SHAPE represents ROBUSTNESS**

CORRELATION

- **Expresses the STRENGTH OF THE RELATIONSHIP Between Variables**

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Correlation

- CORRELATION - A CONCEPT THAT SUPERSEDES SENSITIVITY
- CORRELATION BETWEEN TWO VARIABLES
  - SHOWS THE STRENGTH BETWEEN VARIABLES
  - TAKES SCATTER IN ALL OTHER VARIABLES INTO ACCOUNT.
- CORRELATION BETWEEN ANY PAIR OF VARIABLES CAN BE COMPUTED
  - INPUT - OUTPUT
  - OUTPUT - OUTPUT
  - INPUT IS A DESIGN OR NOISE VARIABLE
  - OUTPUT IS A PERFORMANCE, LIKE STRESS OR FREQUENCY
- KNOWLEDGE OF THE CORRELATIONS IN A SYSTEM LEADS TO UNDERSTANDING HOW THE SYSTEM WORKS

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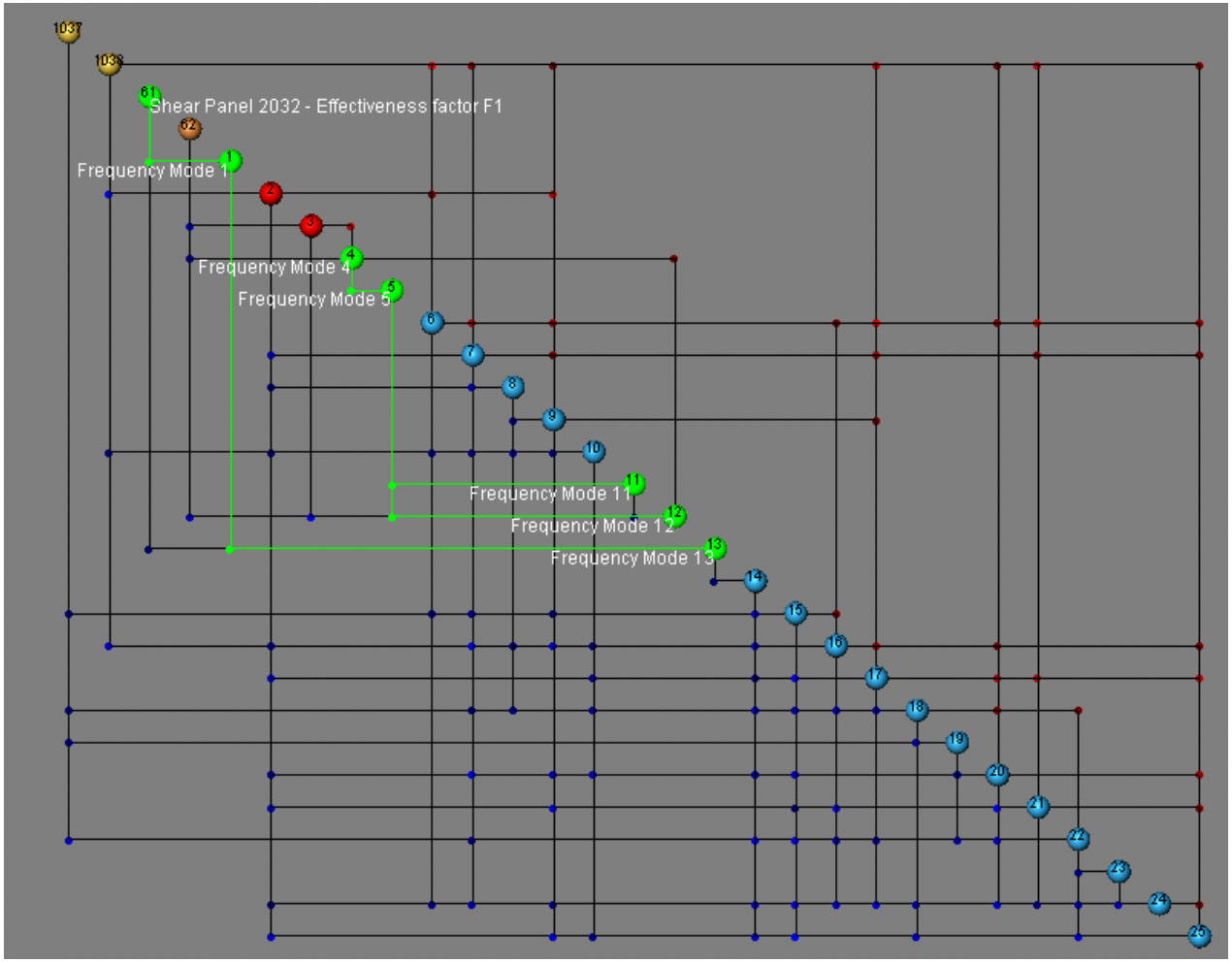
The Decision Map



The decision map reflects how all system attributes react t small simultaneous changes in all of the input variables.

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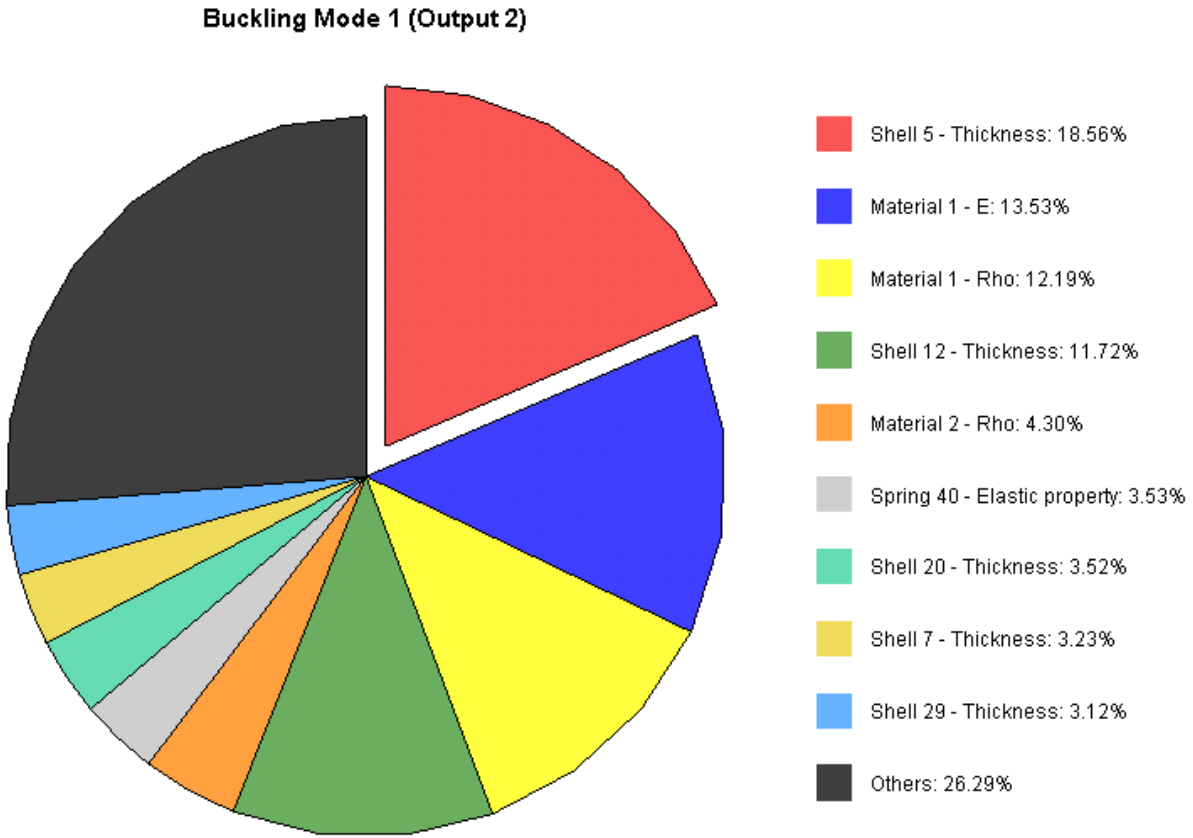
Variable Ranking (Spearman)


Buckling Mode 1 (Output 2)
Shell 5 - Thickness: 18.56%
Material 1 - E: 13.53%
Material 1 - Rho: 12.19%
Shell 12 - Thickness: 11.72%
Material 2 - Rho: 4.30%
Spring 40 - Elastic property: 3.53%
Shell 20 - Thickness: 3.52%
Shell 7 - Thickness: 3.23%
Shell 29 - Thickness: 3.12%
Others: 26.29%

Spearman variable ranking allows to determine where the e
effort must be concentrated and where tolerances may be r

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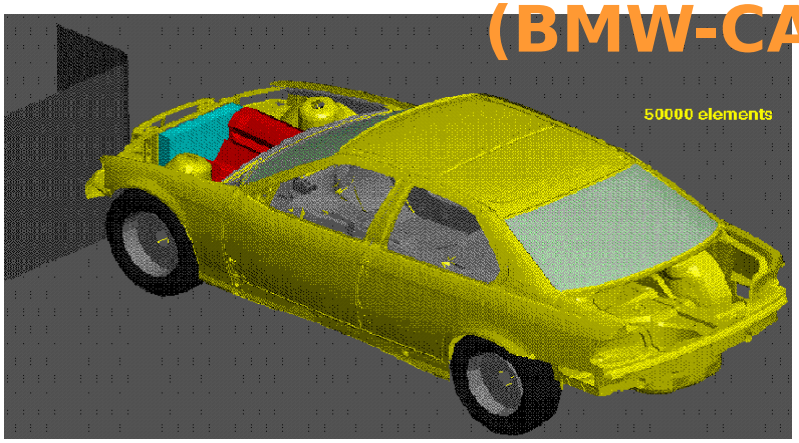
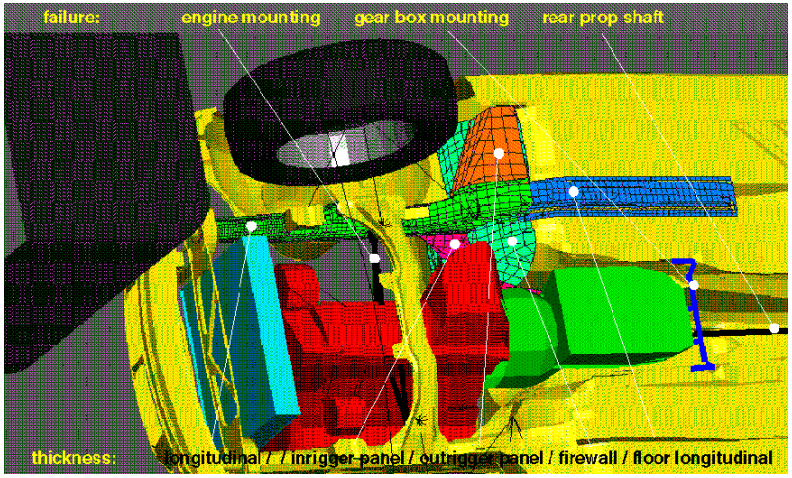
First World-wide Stochastic Crash

(BMW-CASA, August 1997)



- Stochastic material properties, thicknesses and stiffnesses (70 variables),initial and boundary conditions (angle, velocity and offset).
- 128 Monte Carlo samples on Cray T3E/512 (Stuttgart Univ.)
- 1 week-end of execution time.



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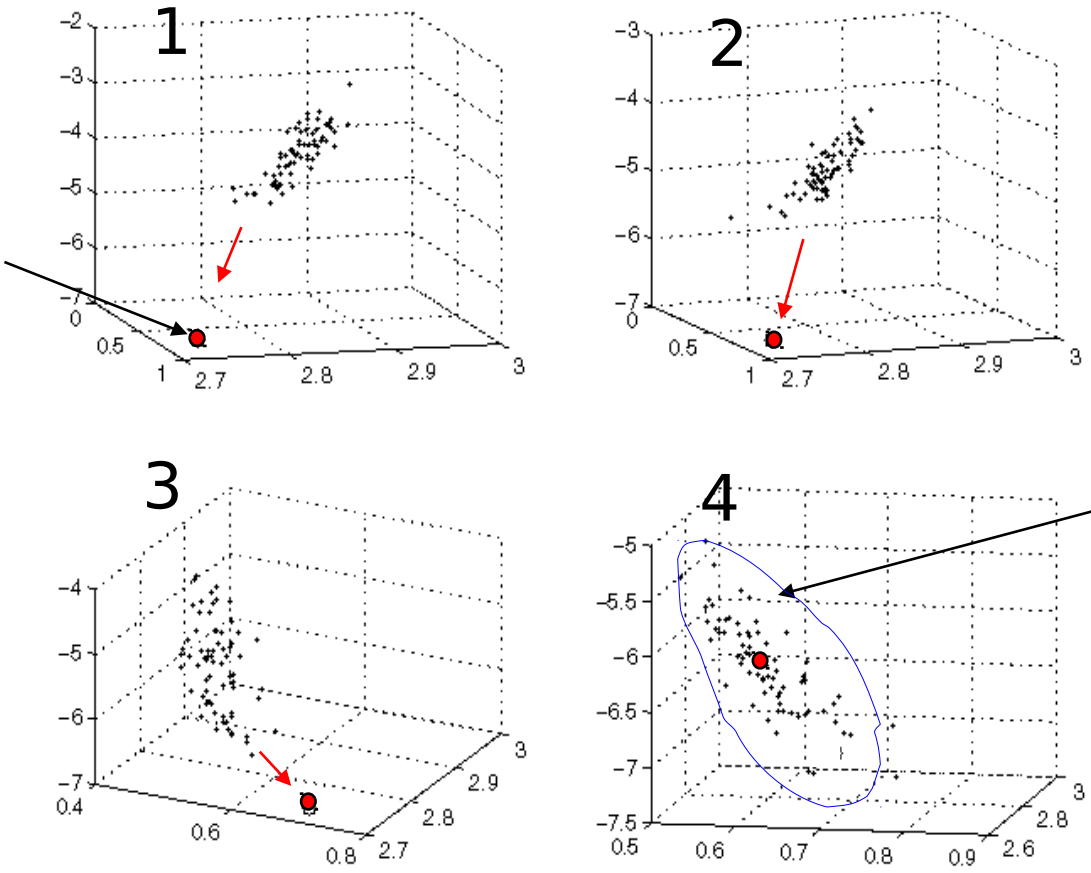
Stochastic Design Improvement

Target location of meta-model (mean of tests)



Improved meta-model

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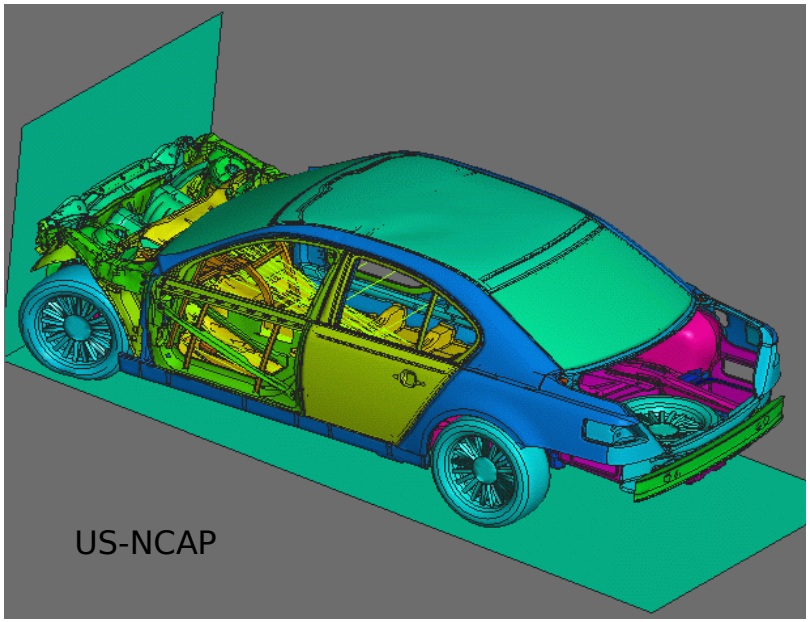
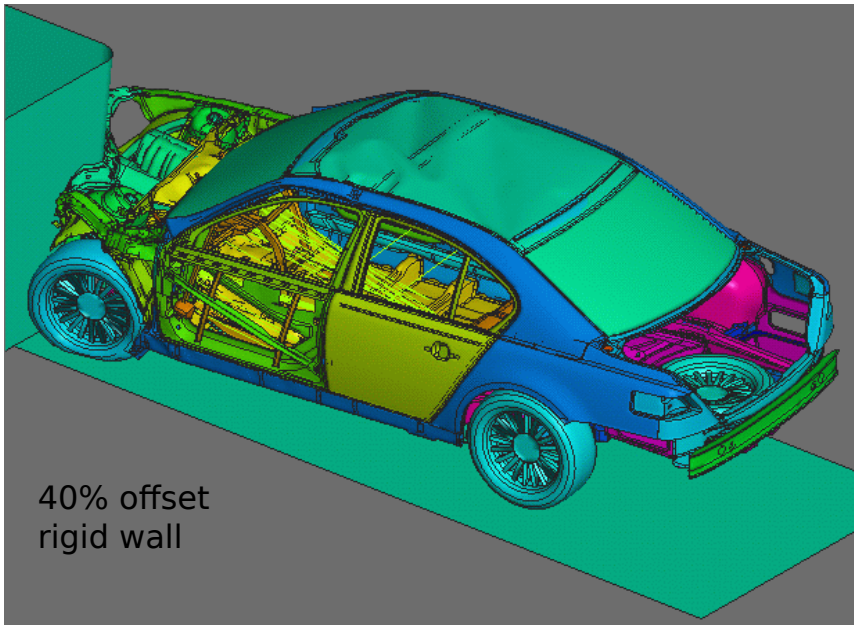
Stochastic Design Improvement





Courtesy of BMW AG

Problem: Reduce weight by 15 kg without reducing performance

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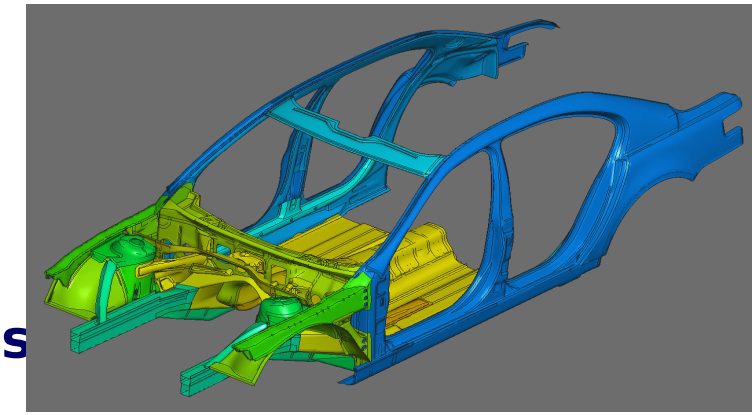
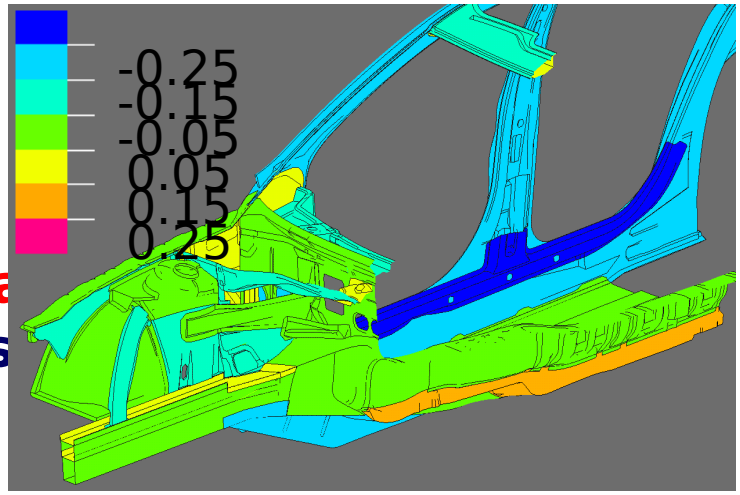
Stochastic Design Improvement



Initial design

Deformations (mm) **Mas**
(kg)
12, 20, 47, 88, 103, 4, 9, 39, 82
184.6



Final design (Improved, not Optima

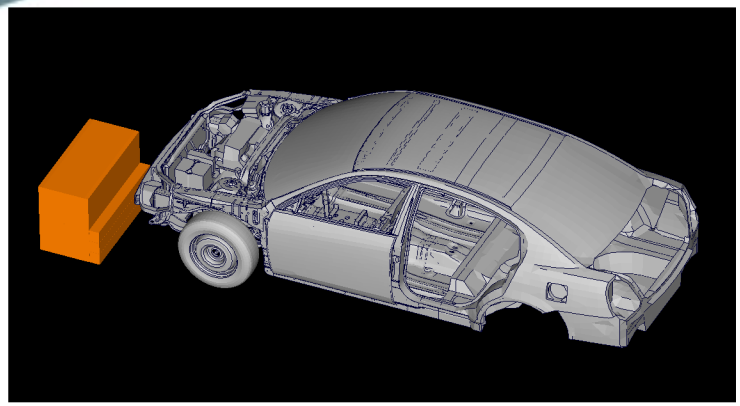
Deformations (mm) **Mas**
(kg)
17, 23, 49, 87, 108, 6, 10, 46, 86
169.3

Courtesy of BMW AG

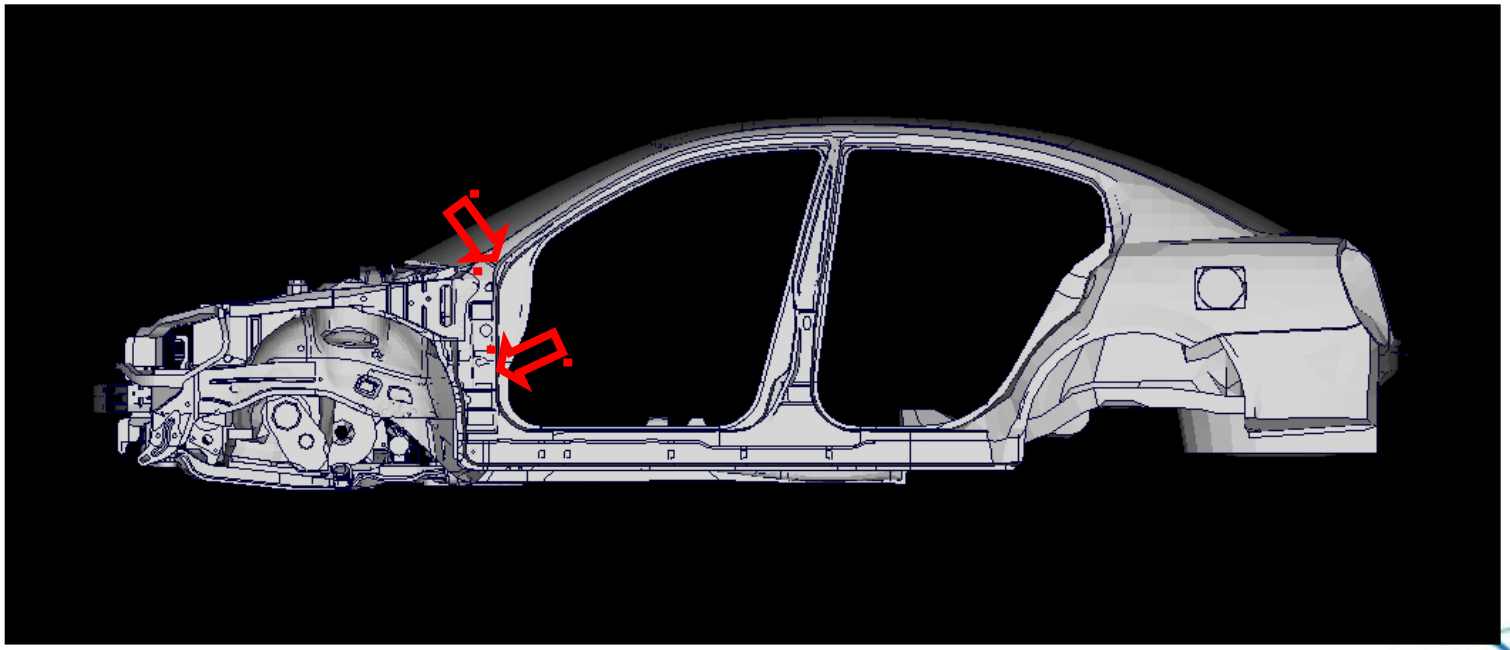
This analysis took 90 executions of 200 hrs each. 33 lbs of saving per car is equivalent to $33. In 5 years, this means $36 M. The job can be run in 3 days on 256 CPUs.

MSC SOFTWARE
SIMULATING REALITY

Stochastic Design Improvement



Problem: reduce mass, maintain safety a
stiffness
Result:
16 kg mass reduction
20% reduction of A-pillar deformation
40% reduction of dashboard deformatio
Cost = 60 runs (tolerances in all materia
thicknesses) of PAM-Crash and MSC.Nas



Courtesy, Nissan Motor Company

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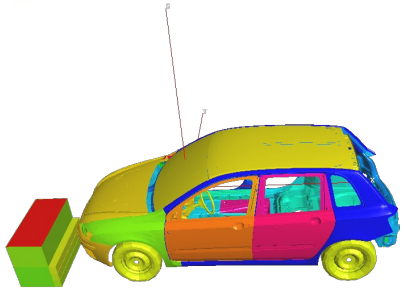
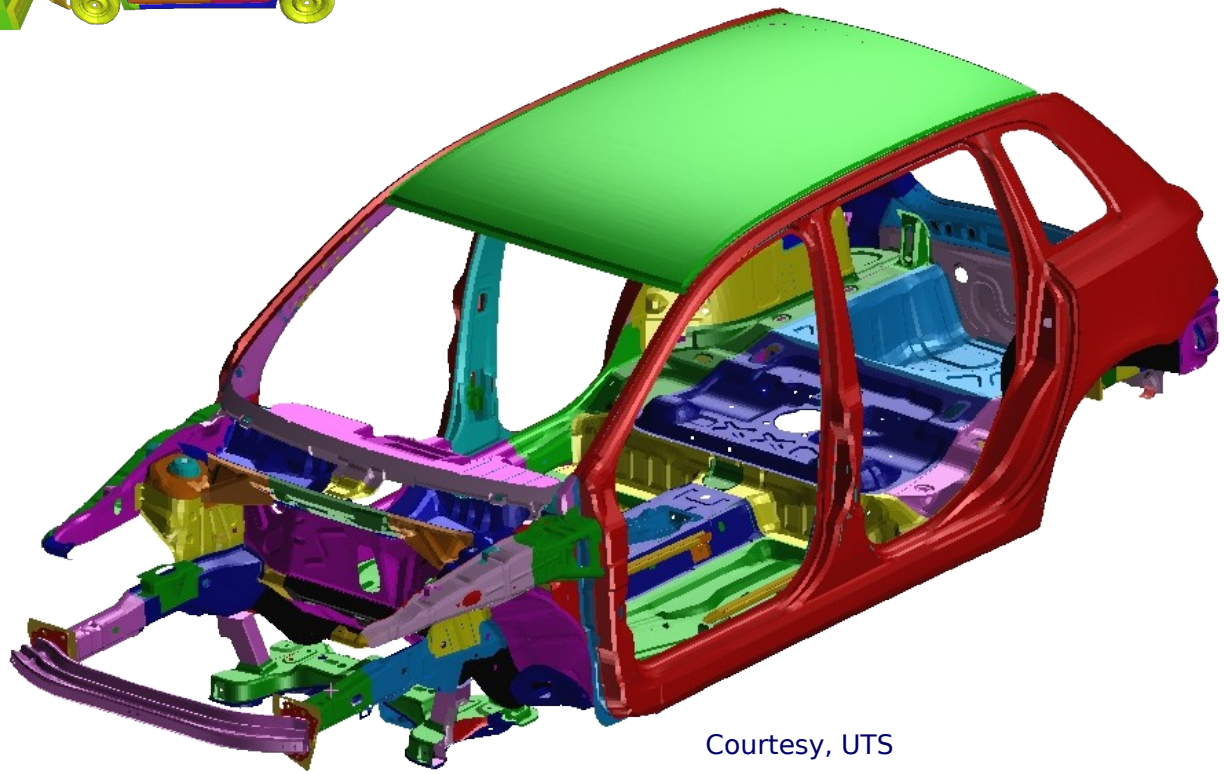
SIMULATING REALITY

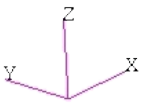
Stochastic Design Improvement



Problem: reduce mass, maintain safety and stiffness
Result:
10 kg mass reduction
Cost = 85 runs of PAM-Crash and MSC.Nastra



Courtesy, UTS



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SIMULATING REALITY

Automotive Investment in Stochastic Crash Simulation

- **Have Continued to INVEST since 1997**
  - **Have bought High Performance Computing Clusters for Stochastic Car Crash Simulation**
- **Present level of Central Processing Units (CPU) dedicated to Stochastic Simulation (by company):**
  - **BMW – 300**
  - **Audi – 256**
  - **Toyota – 300**
  - **Jaguar – 48**
  - **Mercedes – 384**
  - **Nissan – 128**

Evidence of Buy-in / Cost Savings Realized

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SIMULATING REALITY

Automotive Design Improvements from Stochastic Crash Simulation

MASS REDUCTION RESULTS with SAME OR BETTER CRASH PERFORMANCE

- **Car Model 1 – 55 lb/car --- saved > $55 Mil**
- **Car Model 2 – 35 lb --- > $35 Mi**
- **Car Model 3 – 40 lb --- > $40 Mi**
- **Car Model 4 – 33 lb --- > $33 Mi**
- **Car Model 5 – 13 lb --- > $13 Mi**

- **1 lb mass reduction yields $1 per car**
- **Given 1 million cars made per model**

Evidence of Buy-in / Cost Savings Realized

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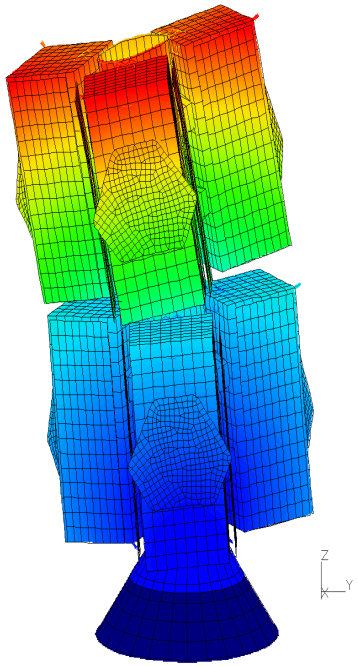
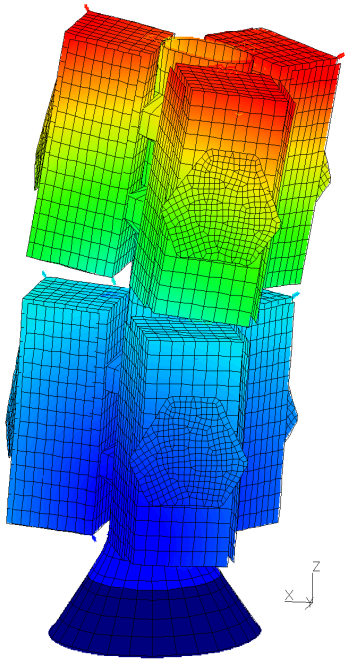
SIMULATING REALITY

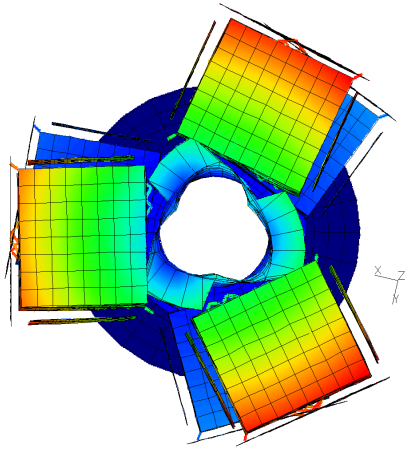
Satellite dispenser

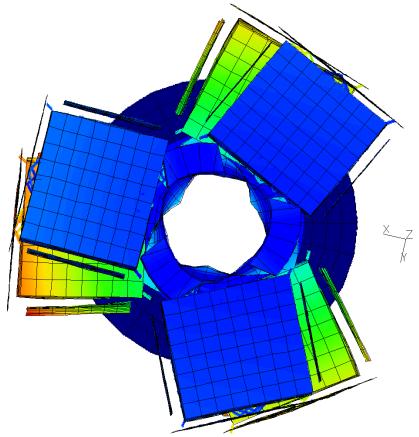


MODE 1 (9.7Hz)



MODE 2 (9.74Hz)





Courtesy EADS-CASA

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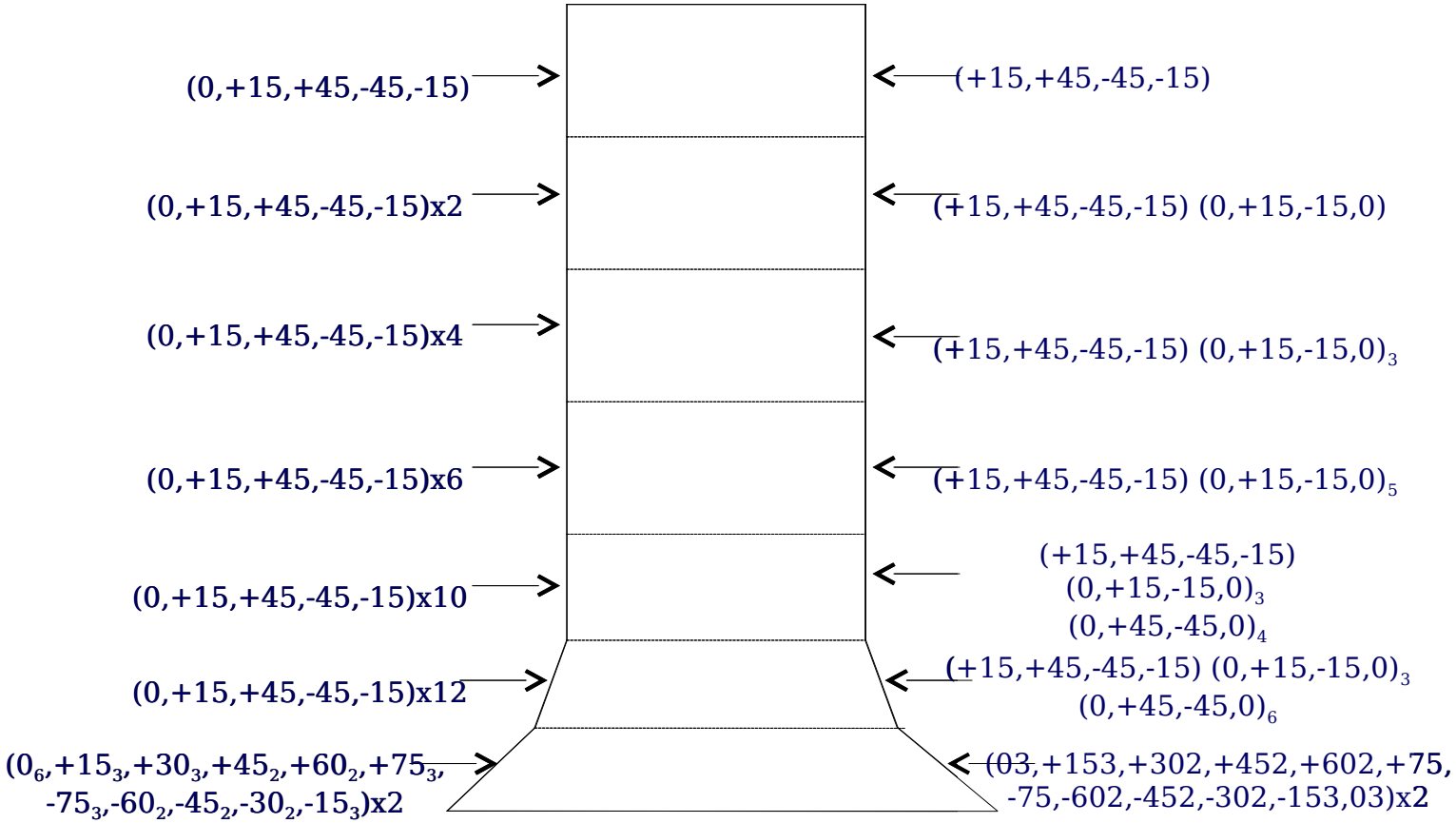
SIMULATING REALITY

Satellite dispenser

INITIAL CONFIGURATION

TUNED CONFIGURATION



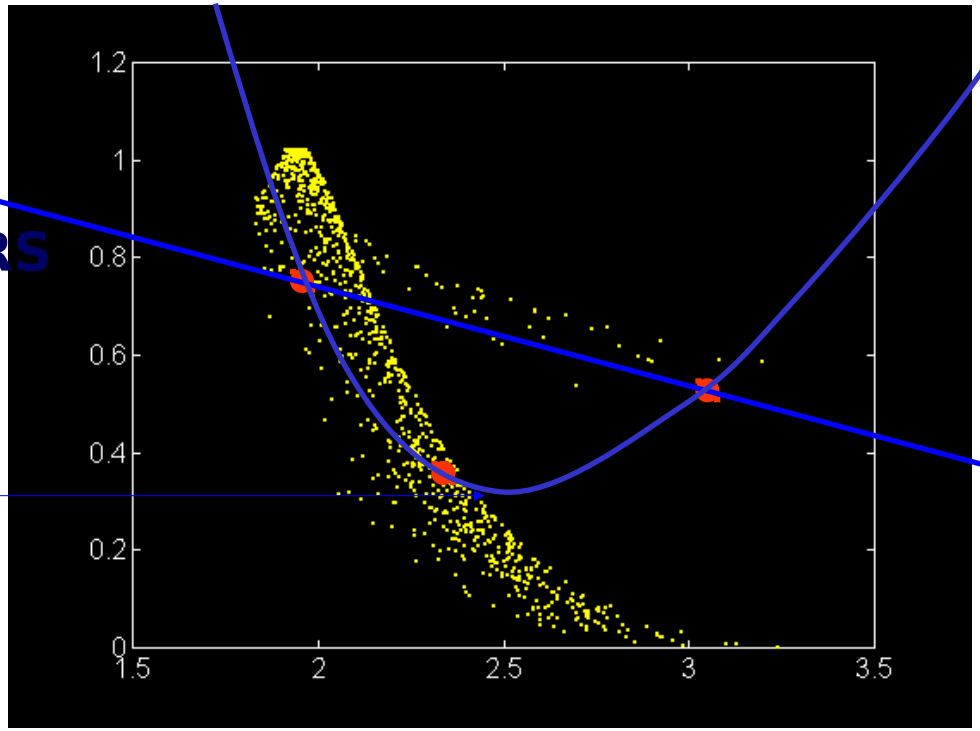
Mass= 436 kg
f1= 9.7 Hz
(200 kg are metallic parts
Not active in SDI)

Courtesy EADS-CASA

Mass= 362 kg
f1= 9.47 Hz

FTWARE
SIMULATING REALITY

Improved Engineering



Second order RS

First order RS

Optimum?

Different theories can be shown to fit the same set of observed data. The more complex a theory, the more credible it appears!

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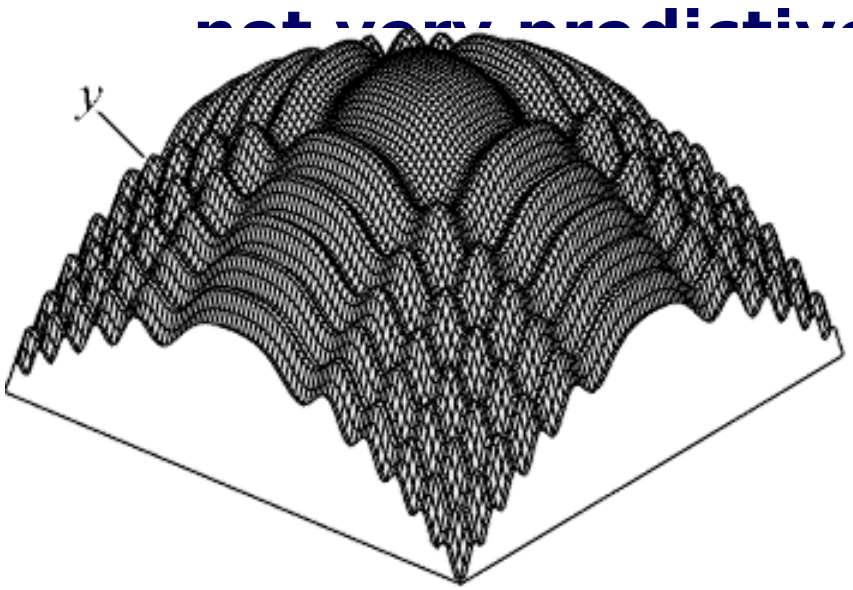
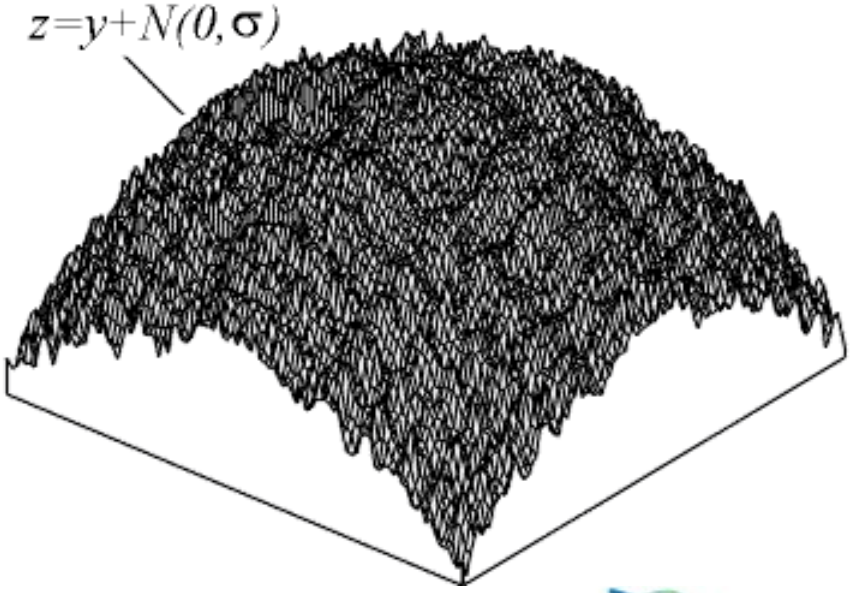
SIMULATING REALITY

Improved Engineering
Reality versus Surrogates

- When the most common forms of uncertainty are incorporated, many optimization techniques don't work. Therefore, surrogate models are used, which are not very realistic (therefore not very predictive!





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Improved Engineering
Remedies against risk

- **Don’t optimise (leads to fragile designs)**
- **Design for robustness instead**
- **Design for less complexity (possible via proprietary methodologies)**
- **Search for potential pathologies**
- **Incorporate uncertainty into models – deterministic models by definition induce unjustified optimism**
- **Understand how (complex) systems really work – compute knowledge!**

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Conclusions

Stochastic Simulation Reduces the Complexity in Modeling Reality

- **Addresses Uncertainty and Variation**
  - **Establishes credibility in modeling & simulation**
- **Easy to use**
- **Focuses on Robustness vice Optimization**
  - **No assumptions of continuity**
  - **Takes all inputs into account vice needing initial assumptions**

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